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DESIGN OF AN EXOSKELETON WITH KINESTHETIC FEEDBACK: LESSONS LEARNED[1]

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ABSTRACT

The Harry G. Armstrong Aerospace Medical Research Laboratory (AAMRL) initiated a project to design a teleoperator master controller which progresses towards the telepresence goal of intuitive operation. A study of past teleoperators shows that the human's ability to control a kinematically redundant slave robot is not fully used with existing devices: either the master system does not consider the human's solution to the redundant degree of freedom, or the human's kinesthetic sense is eliminated, or both. The AAMRL project designed a bilateral (force-reflecting) exoskeleton which would allow the operator to use both of these attributes during teleoperation. The design process was hindered by a lack of fundamental biodynamic data, which had to be synthesized from other studies. Areas of human performance research are identified to verify the biodynamic assumptions made during this project. Areas of manipulation research, using a kinematically redundant slave robot, are also described to quantify the expected improvements in telemanipulation resulting from the kinesthetic feedback provided by this exoskeleton.

INTRODUCTION

Telepresence may be described as teleoperation with high-fidelity feedback of all needed senses to the system operator. One view of telepresence is as an extension of current telemanipulation technologies to include visual, force, kinesthetic, tactile, and aural subsystems [1]. It is envisioned that telepresence, by virtue of its (ideal) intuitive operation, will allow remote manipulators to perform an expanded range of tasks in environments that are hazardous to humans, without needing to be programmed for each situation. As the multiple sensory feedback technologies mature, these remote tasks may be performed in environments which are less structured and more highly dynamic, taking advantage of the human operator's improved comprehension of the task state [2].

This paper describes a recent design effort in the Robotic Telepresence program at the Harry G. Armstrong Aerospace Medical Research Laboratory (AAMRL). The purpose of this effort was to design a force-reflecting master controller which progresses towards the telepresence goal of intuitive operation. Program management and much of the human factors research was conducted at AAMRL, with engineering work accomplished by Systems Research Laboratories and Martin Marietta Aero & Naval Systems (MMANS). MMANS also provided human factors expertise on the project. This paper describes significant details from the design project, beginning with an examination of several past telemanipulation master controllers. This leads to performance criteria for the new master controller. Next, specific findings from the design process are presented. Finally,

[1]The author is indebted to Mark S. Jaster for his innovative thinking and tireless efforts. Without him this work would not have been possible.

subsequent areas of biodynamic and manipulation research are discussed. This research is vital to validate assumptions made during the project and to determine the utility of this type of controller during remote manipulation.

BACKGROUND

The following section examines the operator's interface to teleoperated systems, and how system performance is influenced by the parameters of the master controller. Refer to Sheridan [3] for a more extensive study of teleoperated systems and their uses.

Review of Past Telemanipulation Master Devices

Discussions of teleoperators generally begin with Goertz. The Model 1 Manipulator was an innovative application of electro-mechanics to build a laboratory model, force-reflecting positional servomanipulator. Performance of this manipulator was specified as (approximately) 4 lb payload, maximum lineal velocity of 30 in/sec, and stiffness of 10 lb/in [4]. The replica master arm, with 6 degrees of freedom (DOF), was able to be moved with one hand of the operator, using independent positional servos for each joint of the slave.

Much more modern, but less intuitive to operate, master controllers were analyzed by Parsons in his review of the state of the art in industrial robot masters [5]. The controllers for these systems were still at the joystick or pushbutton stage, in addition to software control. Although these controllers were obviously not designed for long-term teleoperation, it is instructive to experience the difficulty in commanding a 6 DOF robot with a 3 DOF rate-controlled joystick, even given sufficient training.

Master controllers designed specifically for teleoperation have progressed significantly since Goertz. New 6 DOF force-reflecting devices have better force sensitivity, less apparent friction, and increased bandwidth from earlier master controllers. The modern devices may be mechanically-coupled replica systems such as the Advanced Servomanipulator at Oak Ridge National Laboratory [6], or electrically-servoed independent systems like JPL's Model X Force-Reflecting Hand Controller [7]. Both of these devices use Cartesian, as opposed to variable rate controlled, motion. Indexing, global stability, and variable compliance are possible with today's devices because of increased computational power in the control loop. Scaling the force-reflection ratio is also possible; in fact, common.

In a semi-structured environment, where the desired end effector and arm segment positions are reachable from the current positions without environmental interference, the 6 DOF devices described above are sufficient for manipulation. However, in an unstructured environment, where obstacles may be located between the current and desired positions, 7 DOF may be needed for some tasks. None of these 6 DOF master controllers allow the operator to use the human arm's redundant DOF to manipulate a slave arm around obstacles.

At least one master controller was made which allows the human operator intuitive control of a redundant DOF. This device is the MB Associates (MBA) exoskeleton described in ref. [8]. Because this exoskeleton is closely coupled to the operator's arms, the kinematic solution to the redundancy is realized immediately by the shoulder/elbow angles. This solution is only important when a kinematically-similar slave robot is controlled, and the operator's redundant solution is mimicked by the slave. Otherwise, the information is unusable. But the MBA exoskeleton has

a major drawback from current 6 DOF master controllers: the operator receives no kinesthetic feedback from the slave robot.

The AAMRL project hoped to match the performance of the recent 6 DOF bilateral master controllers, and add the ability to use the arm's redundancy for obstacle avoidance in unstructured environments. The following section describes the criteria used in the design of this new controller.

DESIGN GOALS

The design of master controllers usually begins with an identification of the tasks expected to be performed by the system. From this task analysis, key performance requirements for the system are discerned. After these requirements are specified, the mechanical design begins. A recent example of this task analysis - requirements definition - mechanical design process is occurring in the development of NASA's Flight Telerobotic Servicer. See [9] for a good example of this type of design process.

AAMRL deviated from the above process in designing the new master controller. The goal of the new design was to develop a master controller with performance analogous to a human operator in general, not for specific tasks. Therefore, the design did not begin with a task analysis. The performance requirements for the controller, instead, remained broadly biophysical: the manipulator would be expected to move throughout a human's workspace, at human velocities and accelerations, while supporting itself and reflecting a pre-defined range of forces from the slave manipulator.

Performance Criteria for the New Master Controller

The following requirements (a subset of the complete design criteria) were determined to be adequate performance goals for the new master controller [10]:

- Kinematically similar to a human, including DOFs and ranges of motion.
- Size adjustable to fit 5th - 95th percentile male and female populations. Linearly adjustable in the shoulder width, elbow resting height, upper arm link length, and lower arm link length. Circumferentially adjustable at each coupling restraint.
- Able to reflect 15 lbs of force throughout the workspace, in addition to supporting its own weight.
- Force sensitive to 2 % or less of maximum force.
- Tuneable force reflection ratio of 1:1 to infinity:1.
- Able to mimic the dynamic response of the human. No discernable phase lag between the master and slave robot.
- Control loop throughput of 4 msec or less.

The above criteria are not all absolute, but empirical data was thought to exist for each requirement. Assuming this data was retrievable, work on a controller design began. Concurrently, a retrieval effort was initiated to gather the human performance data not empirically defined in the performance criteria.

RESULTS FROM THE DESIGN PROCESS

This project resulted in the prototype design of a dual-arm, 7 DOF per arm, bilateral exoskeleton, although several factors significantly hindered the effort. The most surprising hindrance was in the biodynamic data retrieval effort where empirical data is remarkably scarce in the literature. A preliminary design was completed nonetheless, and research has been identified to develop the missing databases. The intent is to validate assumptions made during the design before continuing with construction of this exoskeleton. The following discussion describes those areas where data was lacking, and shows the steps taken to derive the missing data.

Limitations of Existing Human Data and Design Assumptions

Although some biodynamic data are in the literature, much of this data gives arm strength measures over time, for quantifying fatigue. Other data shows joint profiles for simple, one DOF motions (typical of the physical therapy measurement systems). No data was found describing peak joint velocities and accelerations during worst-case arm motion profiles, or individual joint duty cycle information while performing tasks. Without this data it was not possible to accurately determine actuator sizes for the exoskeleton. It was therefore necessary to synthesize this data from other studies.

Estimating Worst-Case Accelerations. Since the appropriate biodynamic data was not found, an attempt was made to approximate the worst-case dynamics of human manipulation. Flash had studied hand motion trajectories, and determined that 300 msec is required for motions (approximately 25 inches) involving the large muscle groups of the shoulder and upper arm, with a nearly bell-shaped velocity profile that supports minimum jerk theory [11]. Similarly, Flash found that shorter motions (approximately 13 inches) take approximately 150 msec. The velocity profiles of these motions were approximated as the piece-wise linear curve of Figure 1. When these curves are integrated over time, and equated with the distance moved, the accelerations and decelerations of the hand can be determined for each motion.

These hand accelerations were then applied to worst-case profiles to determine the peak accelerations of each joint, given the above velocity linearizations. Since no worst-case motion profiles for a human hand were found in the literature, Stoughton's work [12] at Oak Ridge National Laboratories was used to define a preferred hand working volume, coined the Ergonomic Work Space (EWS). Using this EWS (Figure 2), the worst-case motion profiles of Figure 3 were defined. An iterative inverse kinematics solution was used by MMANS to determine the peak accelerations expected at each joint of the exoskeleton [10]. The arm's redundancy was solved by keeping the upper and lower arm links confined to a plane parallel with the gravity vector ("elbow down"), even though this solution may not agree with an actual performance of this motion.

Estimating Joint Duty Cycles. The peak accelerations and velocities were important for motor sizing, but equally important was to determine the rms accelerations, for realistic actuator selection. Stoughton's work [12] was again used to derive duty cycle information for each joint, from which rms values could be calculated. Stoughton had measured the duty cycles of each joint of the 6 DOF SM-229 manipulator at Oak Ridge National Laboratory during typical task performance for this system. Because the exoskeleton being designed contains 7 DOF per arm, another

approximation had to be made in order to arrive at rms accelerations, as follows. The average of the three duty cycles for the wrist of the SM-229 was used for each joint of the exoskeleton's wrist. A more liberal assumption was made for the four remaining joints of the exoskeleton: the average duty cycle for the three large motors of the SM-229 was used for each of the four large motors of the exoskeleton. The accuracy of these assumptions is currently unknown.

Correlating Anthropometric Data. One of the initial performance goals for this master controller was to be adjustable for the 5th - 95th percentile male and female populations. Once work on the exoskeleton design began, however, it was noticed that much of the anthropometric data found in the literature results from non-uniform measurement methodologies. When an attempt was made to correlate the measurements from these various anthropometric databases, it became evident that this correlation project would become extensive. Instead of diverting other efforts to complete this database correlation, a more conservative size specification for the exoskeleton was made: fit the 5th - 95th percentile (Air Force) male populations as defined by several previously correlated databases.

FUTURE WORK TO VALIDATE DESIGN ASSUMPTIONS

A 14 DOF exoskeleton was designed, and a 1 DOF bilateral (testbed) system was constructed based on the exoskeleton's elbow design. Before building the entire exoskeleton, however, the human performance assumptions discussed above must be validated. The following sections introduce research which has begun, or is planned, to find answers to those questions that arose during the design phase.

Measuring Fundamental Biodynamic Data

Empirical measures of human motion must be made to quantify human velocities, accelerations, and torques when both unencumbered and for various loading scenarios. This is the most striking absence in the literature, and it is critically needed for a tightly-coupled device, such as an exoskeleton, to be designed for the extent of human motions.

AAMRL has procured a WATSMART infrared motion analysis system, which is being used to establish specific human performance databases. (Note also that MIT has recently begun biodynamic measures using a similar system [13].) This system can track human motions during the worst-case motion profiles defined above. From these motions, individual joint velocities and accelerations can be derived. Given a sufficiently accurate model of the human arm, of which there are several, the torques exerted by each joint can also be calculated.

With the WATSMART system it is also possible to determine individual joint duty cycles for unencumbered humans, when performing standard tasks. This data, along with the peak acceleration information, applies directly to the actuator sizing for the exoskeleton. The same data can also be analyzed to develop an EWS for those particular tasks.

Comparing Performance Across Device Types

For redundant slave manipulators, it is apparent that a human wearing an exoskeleton, controlling a replica slave, will have less computational requirements than most teleoperator control

schemes. This is due to reduced transforms and an immediate solution to the arm's redundancy. It is not yet apparent whether slave robots which are kinematically similar to a human are feasible for performing any useful telemanipulation tasks.

Once redundant slave manipulators are developed with "human-like" performance, research will be needed to learn whether optimal task performance is achieved by having the slave robot assume the human's solution to the redundancy. Forcing the slave to mimic the human's solution will ideally achieve the same degree of obstacle avoidance that a human would achieve when performing the task hands-on. Another approach to solve the redundancy might be to optimize some other criteria, such as mechanical advantage, energy consumption, or computer-controlled obstacle avoidance. Direct comparisons of task performance must be made between a human wearing a force-reflecting exoskeleton and a human using a kinematically-dissimilar, bilateral master, when each controls a 7 DOF slave. These task performance comparisons should be made in semi-structured and unstructured environments to correlate the comparative task performances with the degree of dexterity required. Work in this area has begun for the dissimilar case [14].

Correlating Anthropometric Data

Comparisons and correlation of anthropometric databases will enable future designs to fit a broader category of human operators, without unnecessarily over-designing because of diverse measurement methods. With the changed demographics of the work force since telemanipulators were first designed, such an approach will be beneficial, and may be required.

LESSONS LEARNED

During the design of the 14 DOF bilateral exoskeleton, the following lessons were learned:

- Empirical biodynamic data is needed for worst-case human joint velocities, accelerations, and torques.
- Duty cycle information is needed for human joints when performing basic motions, and during expected task performances.
- Preferred workspace measurements are helpful for determining worst-case hand motion profiles, and thus joint performance data; empirical workspace data is needed.
- For redundant slave manipulators, tradeoff studies will need to be done between the computationally simpler master-slave approach and computer-optimized solving of the redundant DOF.

CONCLUSIONS

Current telerobotic master devices do not allow an operator to directly control more than 6 DOF while receiving kinesthetic feedback from the worksite. A bilateral, 7 DOF per arm exoskeleton would allow both kinesthetic feedback and redundancy control. Once many human performance questions have been answered, it is hoped a new generation of exoskeleton master controllers will

be able to be implemented, with a combined human/machine efficacy more closely matching that of the unencumbered human. These telerobotic devices may then move telemanipulation out of semi-structured environments and into many of the unstructured environments which are currently hazardous to humans.

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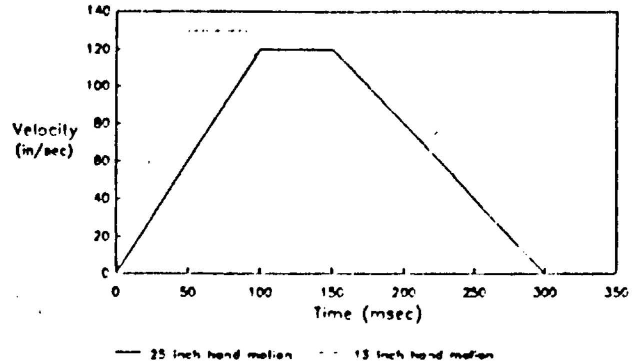
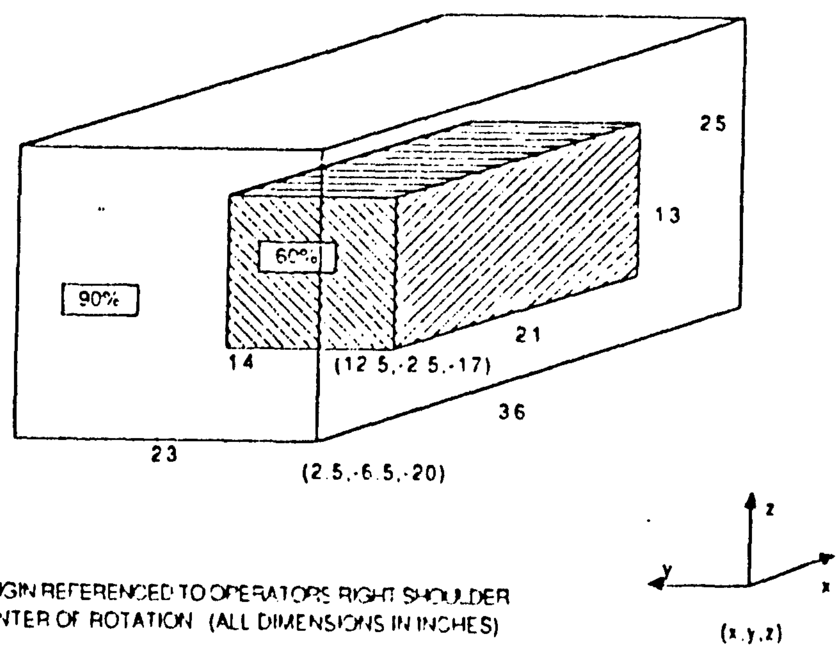


Figure 1 (from [11]) - Piecewise linear approximations to hand motor profiles.

WORK SPACE - HUMAN WRIST PERFORMING 5 ASSEMBLY TASKS

DATA SOURCE - STOUGHTON THESIS , ORNL 1985



ORIGIN REFERENCED TO OPERATORS RIGHT SHOULDER CENTER OF ROTATION (ALL DIMENSIONS IN INCHES)

FIGURE # 2

WORK SPACE - FOUR SIMULATED WRIST TRAJECTORIES

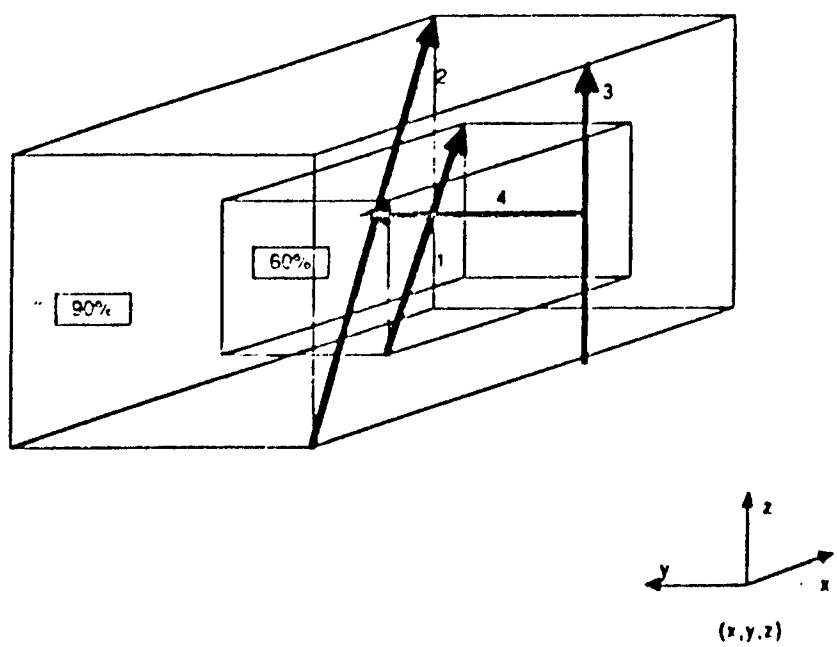


FIGURE 3